Keynote

Design of Next Generation Beam Line Equipment by Applying Advanced Mechatronic Principles

Medsi 2021

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Author: Dr. Ir. Ing. Theo Ruijl

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Partners in Mechatronic Innovation

Founded in 2007

Located in the Eindhoven region, The Netherlands

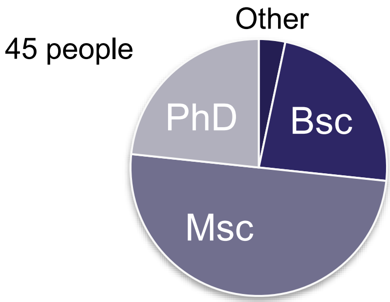
- Cleanrooms, Temp controlled enclosures, low-nose floor, …

Market segments, professional production equipment

– Semiconductor (Wafer scanners, die-bonders)
– Consumer lifestyle (Flat panel layer deposition)
– Analytical and imaging (Electron microscopes)
– Scientific instrumentation (Synchrotron beamlines equipment)

Our working approach:

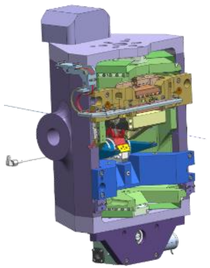
- Use to work on high-risk R&D project
- In close cooperation with customer
- Floating specifications and interfaces
- Understanding use-cases and system interaction
- Design and commit to system performance

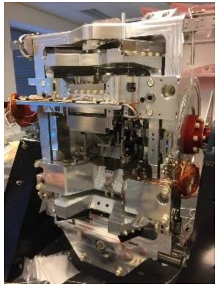


From quasi-static to high dynamic scanning

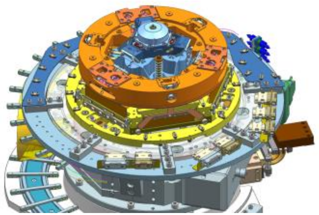
Trent in beamline equipment: applications need fast and high dynamic scanning with nm precision

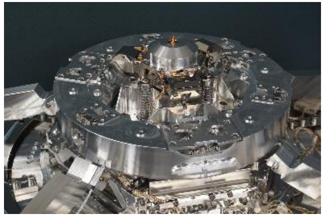
Scanning DCM of LLNS (nrad level)





Sample manipulator fast xy-scanning at fixed Rz (nm level)

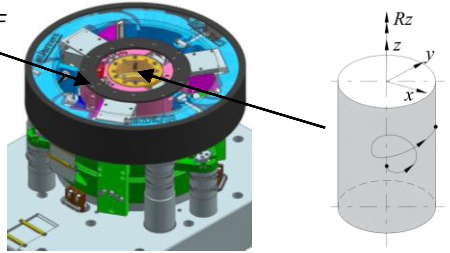




Fast scanning stage for entire wafers (sub um level)

Scanning tomography stage (nm level)

Metrology system 6 DoF
nm level



Scanning [x,y,z,Rz]
simultaneously

Mechatronics in Semiconductor manufacturing

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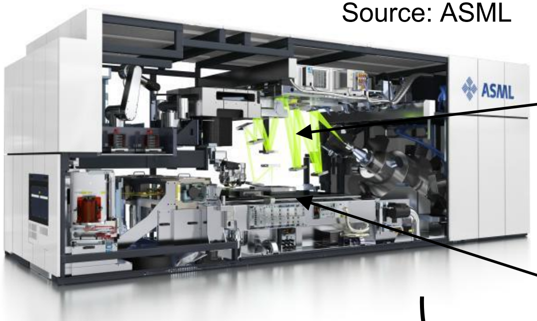
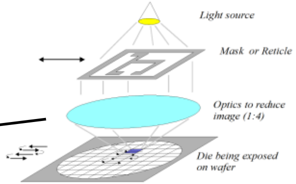
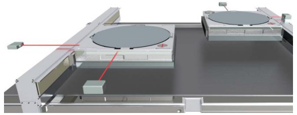
Front-end

Back-end

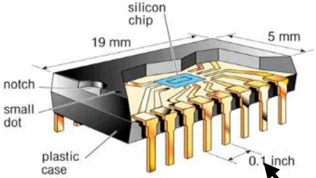
Source: ASML

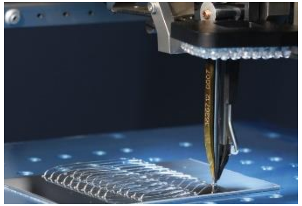


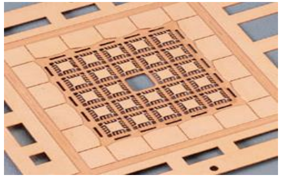


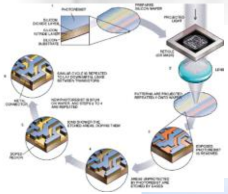


Electrical contacts and packaging

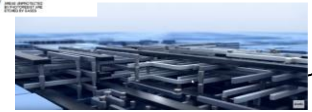




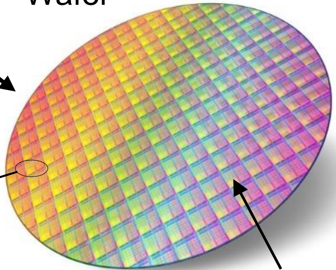




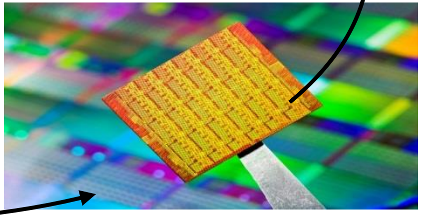
Optical Lithography



Wafer



Die



Dicing

Die bonding: extreme fast 72.000 Dies/hour (= 50 msec/Die)
Stage accelerations x00 m/s^2, with sub um positioning requirements

- Integrated circuits: multi layer devices with nm precision
- 200 wafer/hours
- Stage at x00 m/s^2 and x m/s, with sub nm positioning requirements

Semiconductor Lithography Tool (Wafer Scanner)

Semiconductor Lithography Tool (Wafer Scanner)

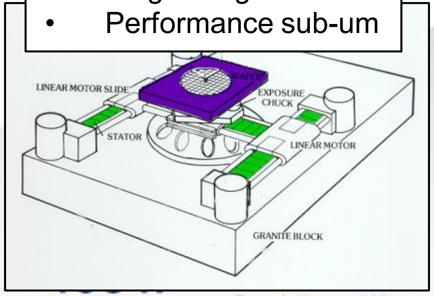
Complexity / technology

PAS 2000
Resolution: >1 µm
overlay: 250 nm

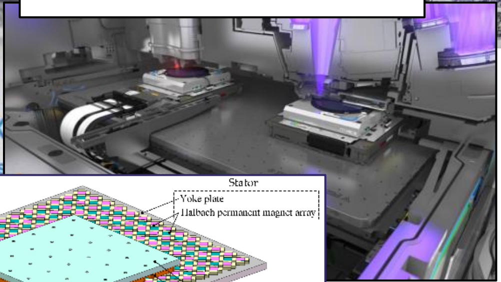
Resolution: <500 nm
overlay: 100 nm

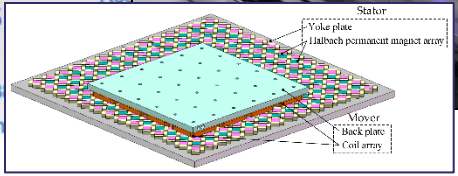
ASML
For engineers who think ahead

H-drive configuration:
- Stepping
- Linear motors
- Air bearings
- Single stage
- Performance sub-um



Planar configuration:
- Continues scanning
- Planer 6 DoF actuator
- Magnetic levitation
- Long/short stroke
- Performance sub-nm





Info from www.ASML.com

www.ASML.com

Accuracy

250nm 100nm 10nm 1nm

Projection Optics: 6 EUV mirrors

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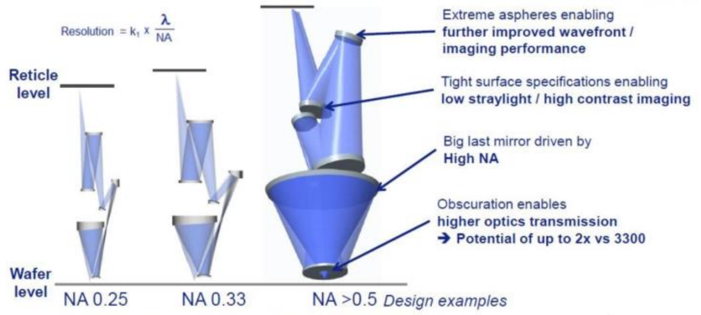
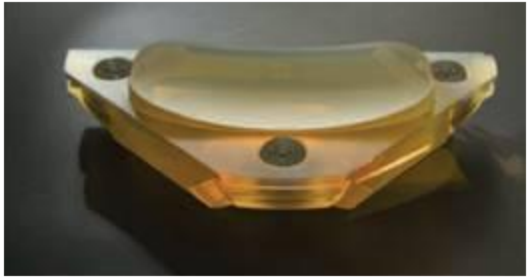
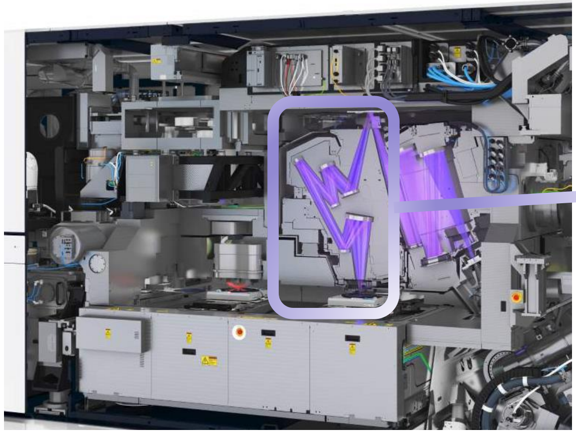
Projection Optics Box:

- 6 EUV mirrors, all fully position controlled (6 DoF)
- Position stability << 1 nrad / 1 nm
- **Position stability reached from active feedback (electro-magnetic actuator)**



Source: Zeiss, "EUV lithography optics for sub-9nm resolution," Proc. SPIE 9422, (2015).





System level mechatronisch design approach

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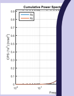
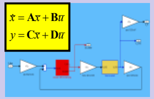
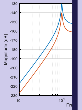
System Architecture
Balancing the design, error budgeting

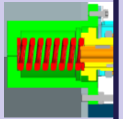
Metrology
System level metrology, sensors and calibration


Dynamics and Control
Servo contro, vibration isolation and damping

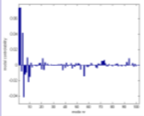




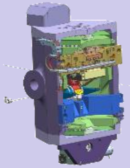
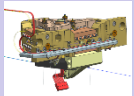
Precision Design principles
Design roles for ultra-precision systems

Thermal
Stability, temperature control, error compensation

Reliability, robustness, …
Design for manufacturing, assembly, …

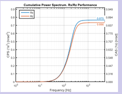



These ultimate performances can not be met by "stacking" standard components, like stage, actuators or sensors.

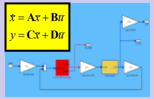
System Level Design Approach →
Understanding and control the system design fully to be able to balance performance.

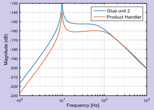
Content of this presentation

System Architecture

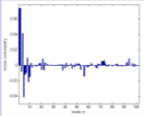


Dynamics and Control





Thermal

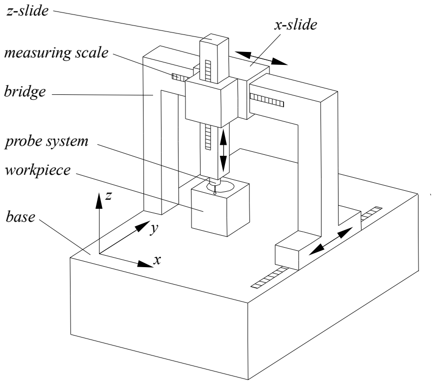


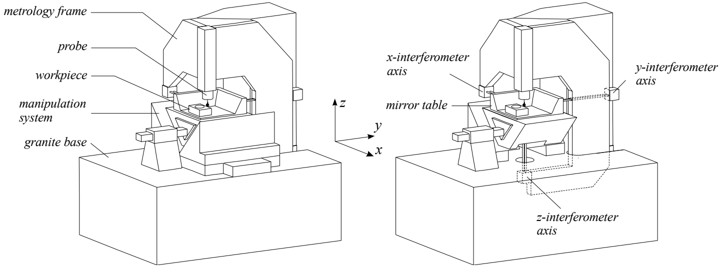
- Dynamic Architecture
- Actuator choice

System Architecture

Ultra-precision and high-dynamic systems:

- Multiple frame architecture
  - Force and metrology frame separation
- Dynamic decoupling
- Isolation of reaction forces
- Long-stroke/ short stroke stage concept





System Architecture

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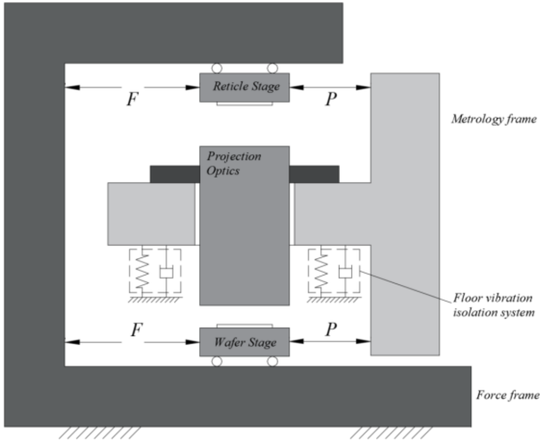
Ultra-precision and high-dynamic systems:

- Multiple frame architecture
- Dynamic decoupling
  - Dynamic separation between fast moving stages and sensitive projection optics on metrology frame
  - 6 dof positioning by active feed back
- Isolation of reaction forces
- Long-stroke/ short stroke stage concept



System Architecture

Ultra-precision and high-dynamic systems:

- Multiple frame architecture

- Dynamic decoupling

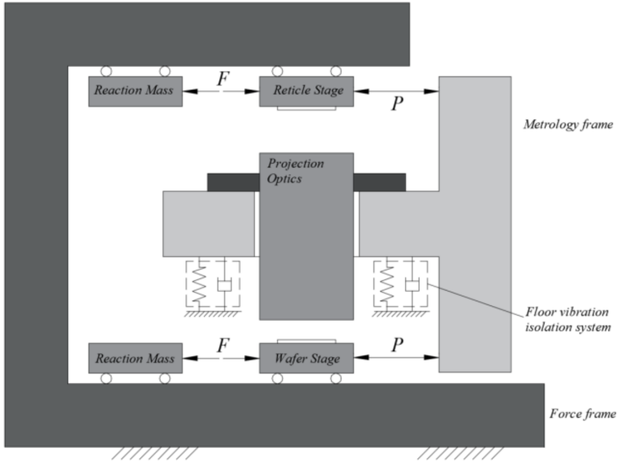
- Isolation of reaction forces

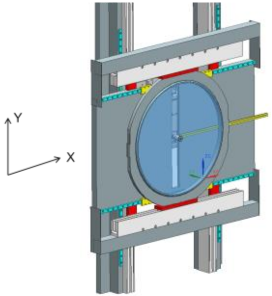
For high dynamic systems, extreme acceleration forces are needed:

  - Reaction forces will excide (via force-frame/floor/isolation system) metrology frame
  - Excitation leads to servo stability issues (dynamics in force frame, so-called reaction path dynamics)

Solution: Reaction (balance) mass decoupling.

- Long-stroke/ short stroke stage concept

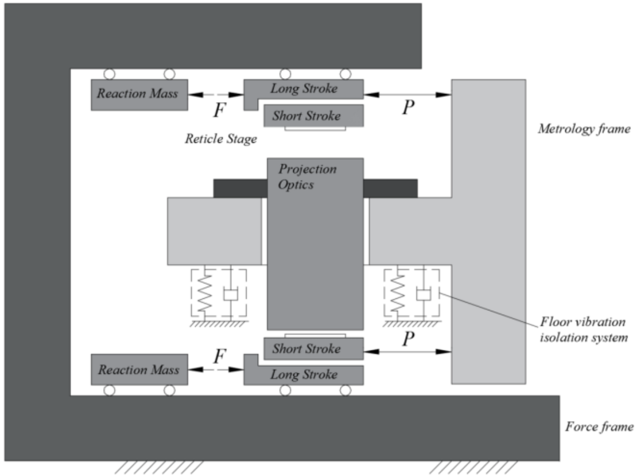


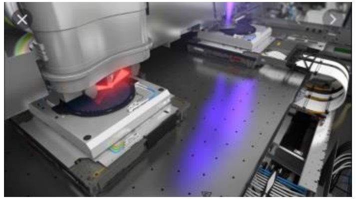


System Architecture

Ultra-precision and high-dynamic systems:

- Multiple frame architecture
  - Force and metrology frame separation
- Dynamic decoupling
- Isolation of reaction forces
- Long-stroke/ short stroke stage concept
  - Long-stroke reaching um level positioning
  - Short stroke reaching nm level positioning



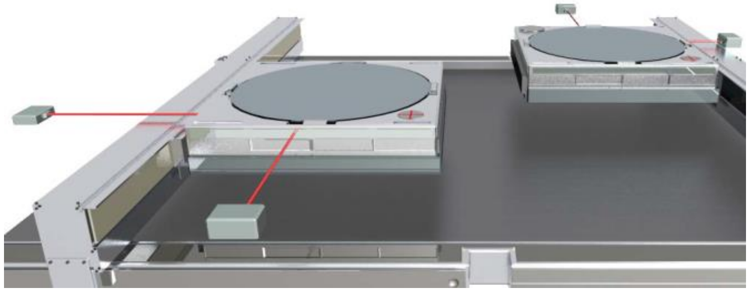


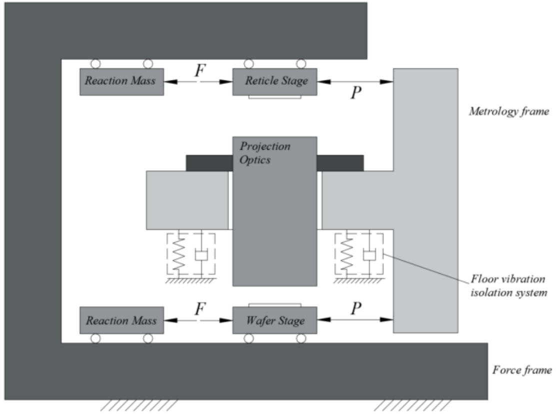
Actuator choice

Behavior of actuator should enable dynamic architecture:

- Long stroke to short stroke configuration
- Reaction mass decoupling

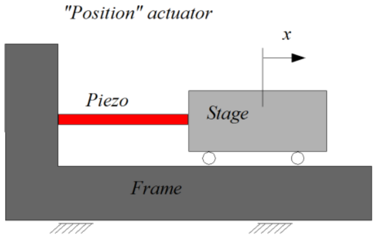
Inherent complaint actuator enables dynamic decoupling



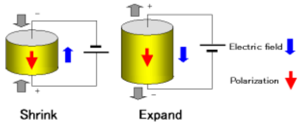


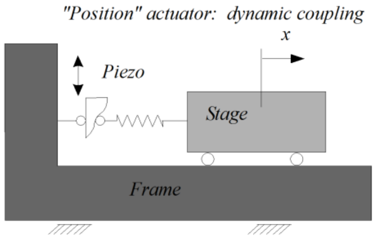
Info from www.ASML.com

Actuators: Dynamics of system with Piezo and Lorentz



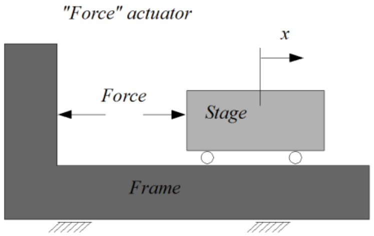
$$\Delta x = f\left(Q_{charge}\right) - \frac{F}{k}$$



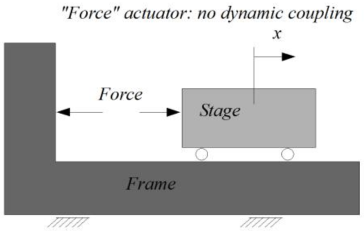


- Dynamic coupling between stage and frame due inherent to stiffness piezo actuator
- Limiting eigen-frequency is stage mass on stiffness of piezo

$$f = \frac{1}{2\pi}\sqrt{\frac{k_{PA}}{M_{stage}}}$$



$$Force = f(I)$$



- Force is only result of current, no inherent stiffness.
- Hence, stage and frame are decoupled, limiting eigen-frequency is internal stage resonance

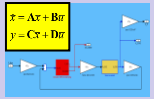
Inherent compliant actuator (e.g. Lorentz):

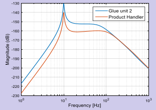
- Decoupled dynamic architecture, enables multiple frame and stage concepts.

Content of this presentation

System Architecture

Dynamics and Control





- Dynamic error budgeting
- Damping

Thermal

Dynamic Error Budgeting as design tool

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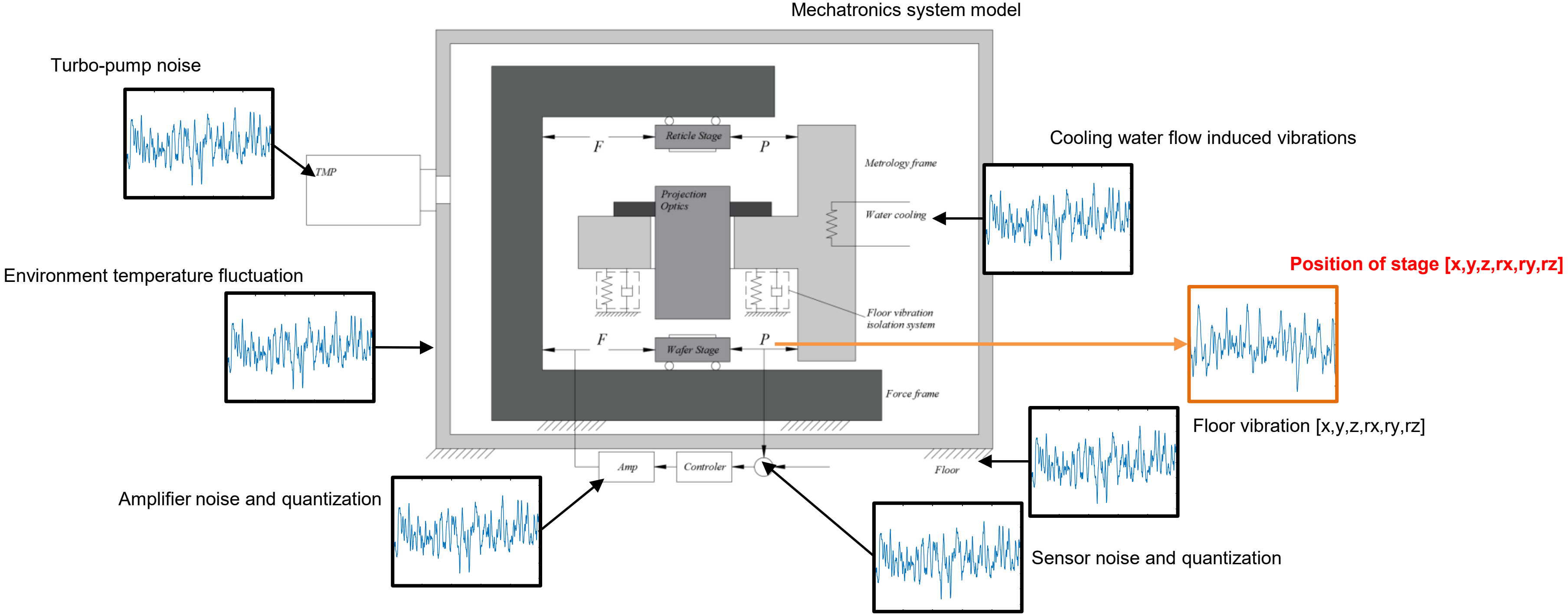
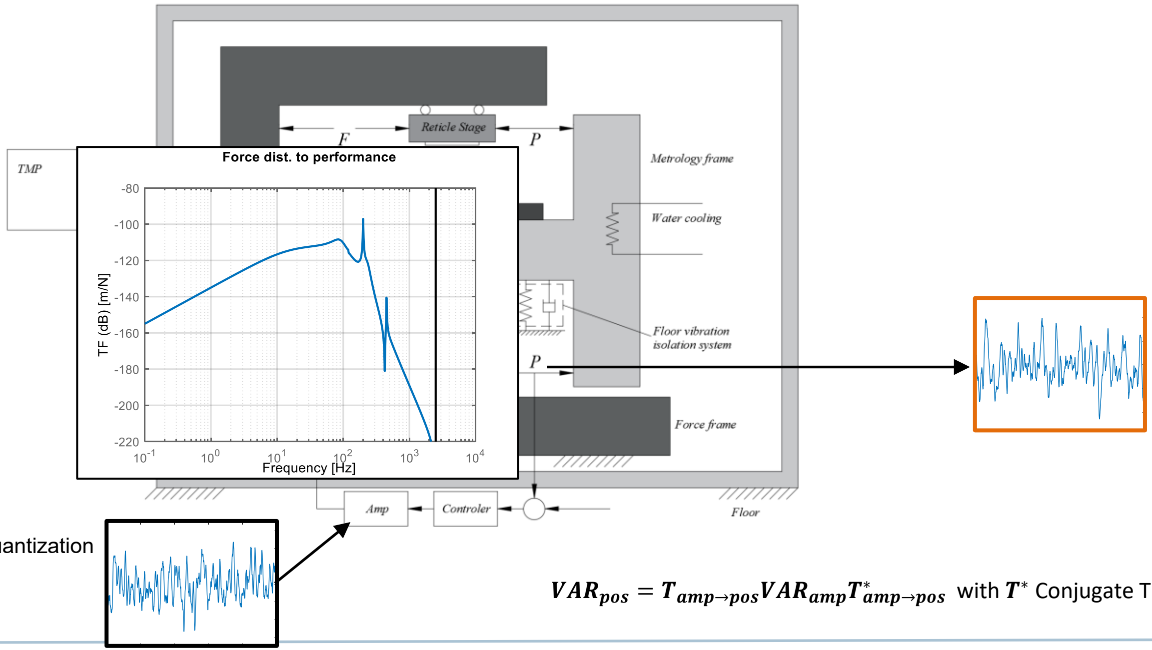
Dynamic Error Budgeting (DEB): way to predict performance of Mechatronic systems.
Objective manner to make design choices.



Dynamic Error Budgeting as design tool

Mechatronic system model links the inputs (e.g. noise sources) to the output (stage position [x,y,z,rx,ry,rz])
Error propagation via Transfer Functions:

Mechatronics system model



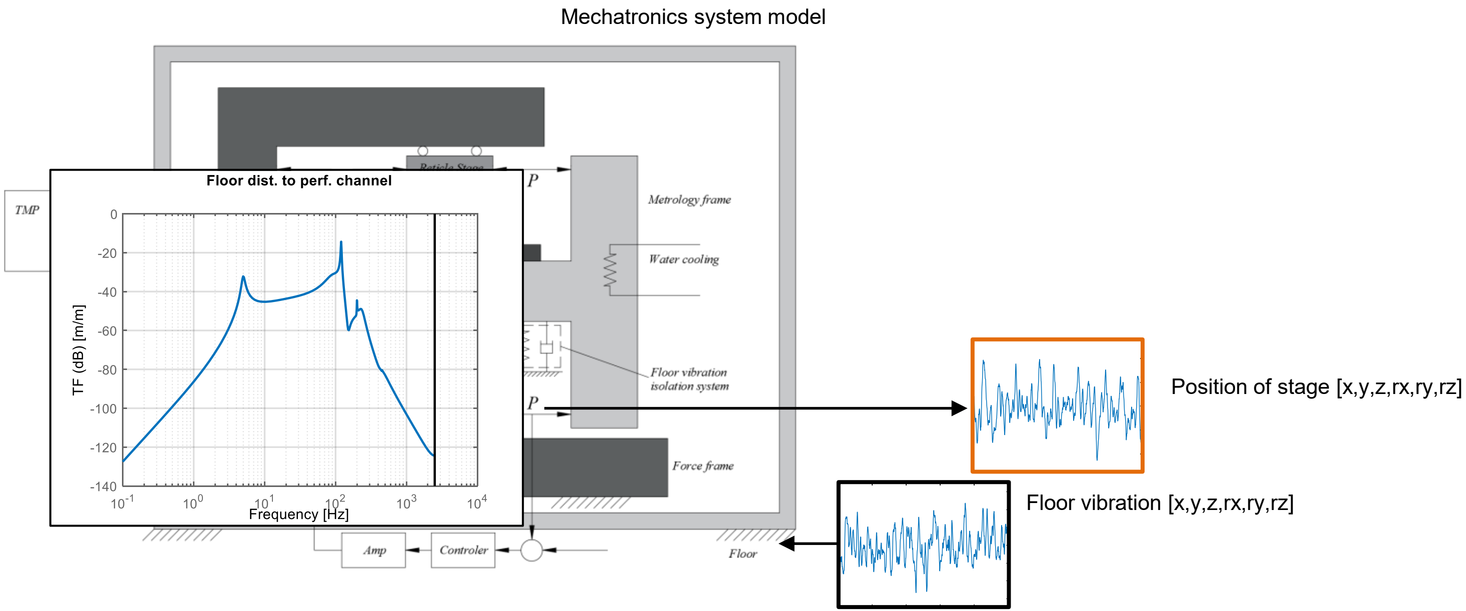
Position of stage [x,y,z,rx,ry,rz]

Amplifier noise and quantization

$$VAR_{pos} = T_{amp\to pos} VAR_{amp} T^*_{amp\to pos}$$ with T^* Conjugate Transposed of T

Dynamic Error Budgeting as design tool

Mechatronic system model links the inputs (e.g. noise sources) to the output (stage position [x,y,z,rx,ry,rz])



Dynamic Error Budgeting as design tool

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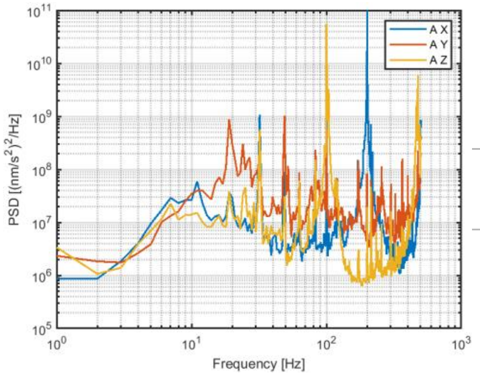
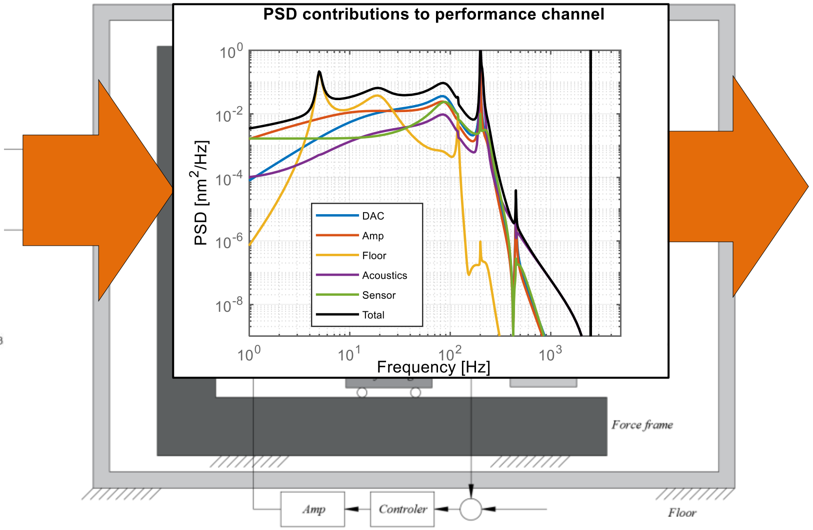
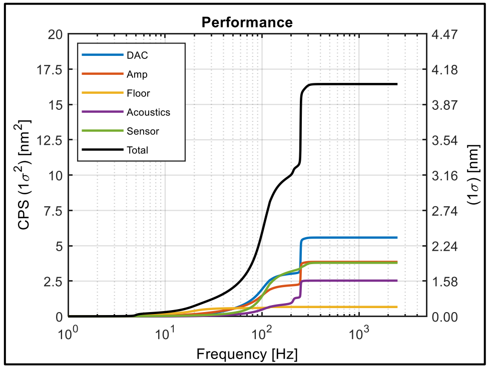
Input: Data in frequency domain, PSD



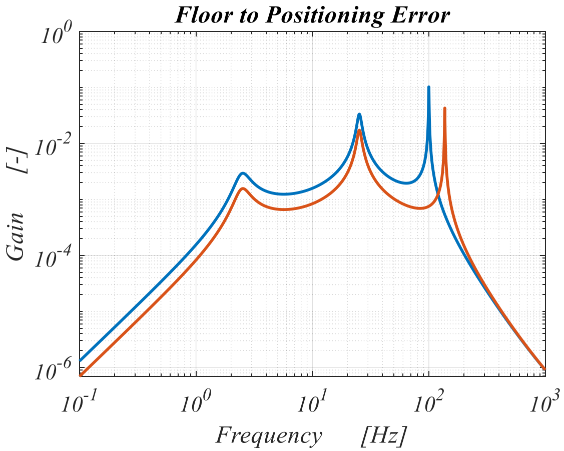


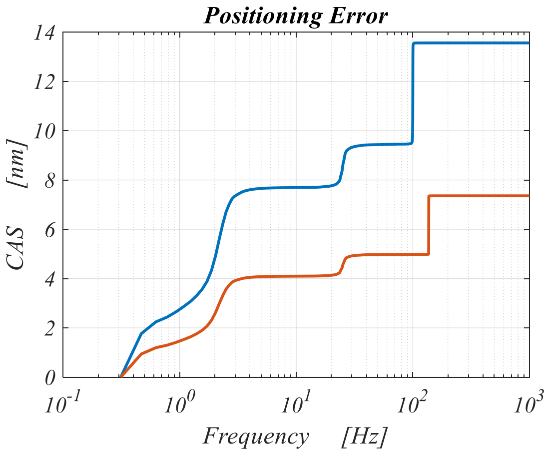
Output: CPS or CAS

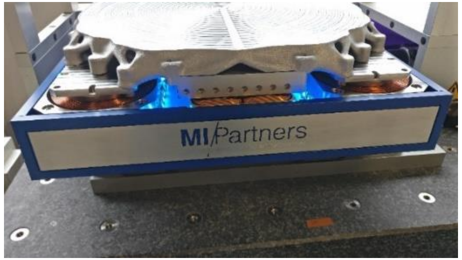


Dynamic optimization

Increasing stiffness and reducing mass:
→ Increasing eigen-frequencies
→ Increasing disturbance rejection



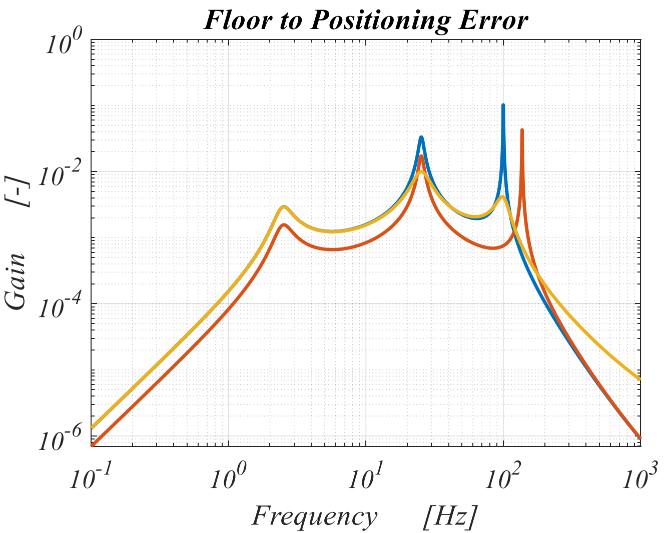


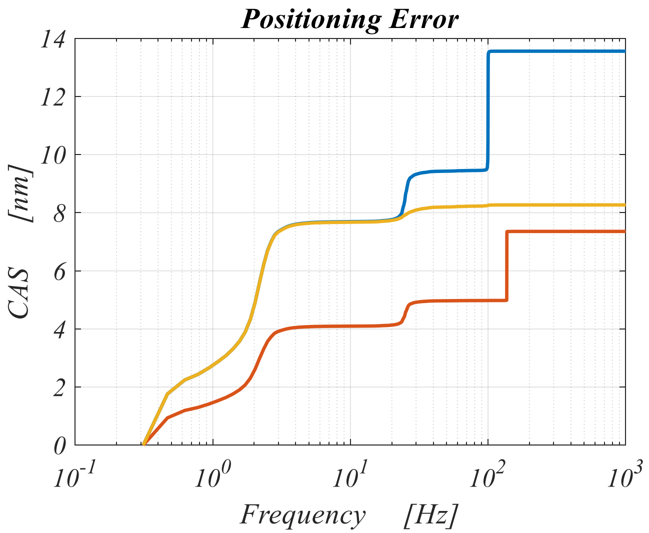


Cuck optimized for dynamic performance:
- Topography Optimization and AM

Increasing damping

Increasing damping, e.g. by means of polymer

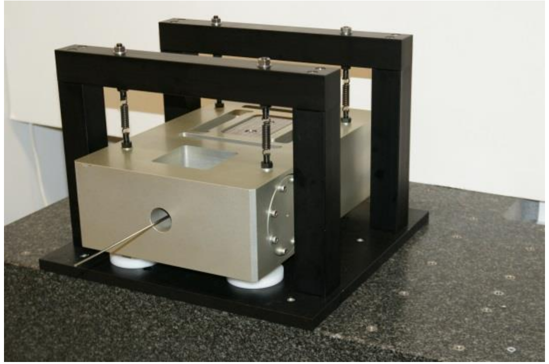


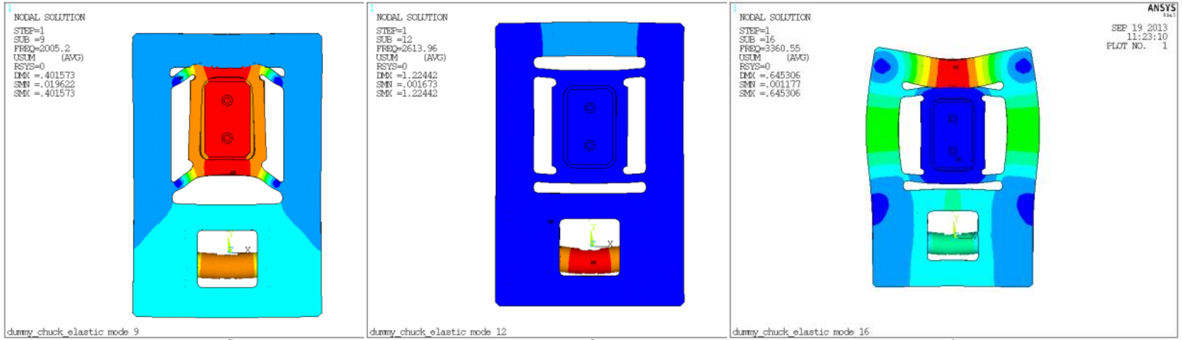


Higher damping

Higher stiffness

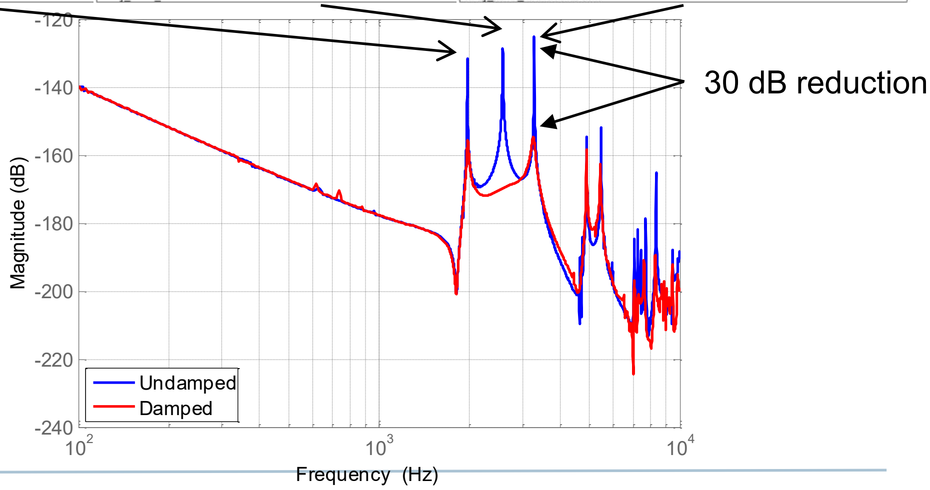
Damped Tuned Mass Damper (High Freq application)





Undamped

Damped



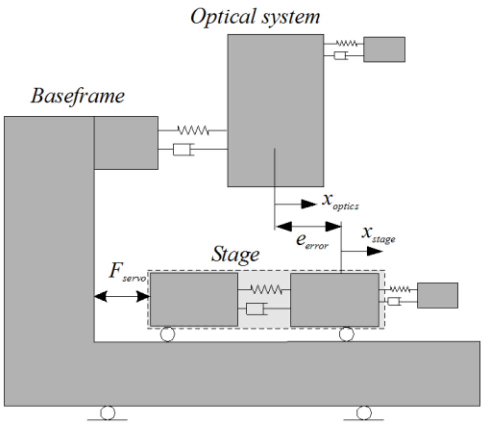
Dominant resonances in 1-4 [kHz] range significantly damped

Damping increases robustness

Not only reduction of disturbance level, but also increasing robustness

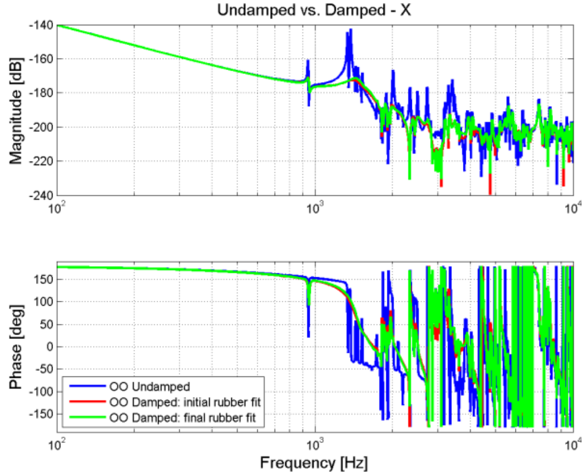
1. Higher servo bandwidth with larger robustness margins
2. Less sensitive to changes in dynamic properties over time (shifting of high frequency peaks)

Real systems have many resonance limiting servo stability



Undamped: high peaks
Damped: lowever peaks and more smooth

$$\frac{X_{stage}}{F_{servo}}$$



Example of high-damping polymer

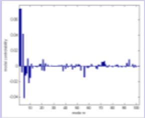
Movie:
Damping

Content of this presentation

System Architecture

Dynamics and Control

Thermal

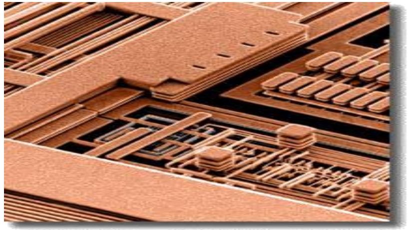


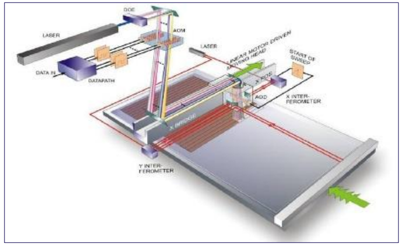
- Thermal error compensation

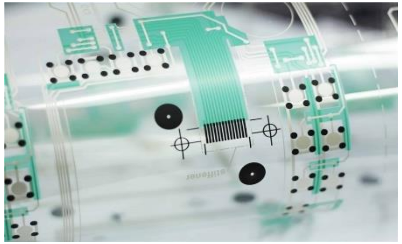
Thermal effects

Thermal effects are one of the largest errors source in high-end precision equipment:

- Larger substrate size
- Higher heat loads from process
- Increasing processing time
- Increasing stability demands (um to nm)

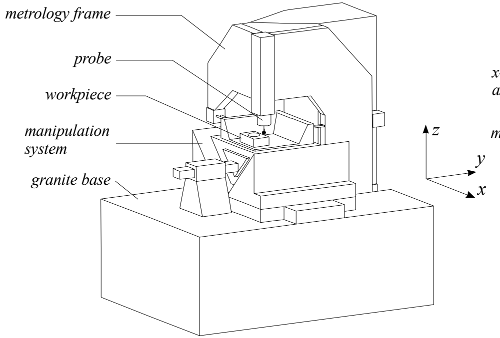


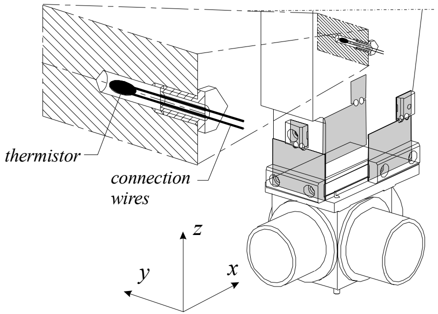


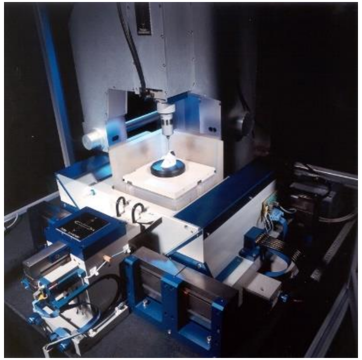


Thermal-elastic Compensation

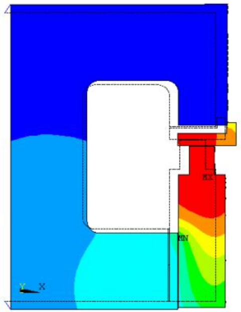
Compensation of thermally induced deformations based on measured temperatures







$$\bar{p}(t) = \mathbf{S} \cdot \bar{T}(t) \quad \rightarrow \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \mathbf{S} \cdot \begin{bmatrix} T_1 \\ \vdots \\ T_n \end{bmatrix}$$



Design and optimisation questions:

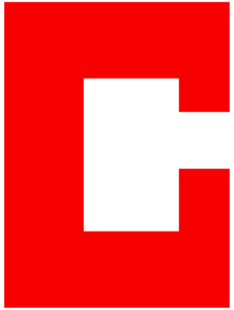
- What are the optimal positions and (minimum) amount of temperature sensors?
- How to find the optimal thermo-elastic compensation matrix $\mathbf{S}$?

Several approaches: “nodal modes” / “eigen modes ” / ”POD modes” / ...

Thermal Compensation strategies: Eigen modes

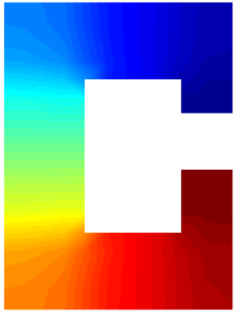
Structural dynamics → Eigen-mode shapes

Thermal system → “Thermal Eigen-modes shapes”



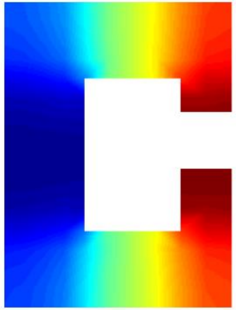
Mode shape 1

Time constant τ_1



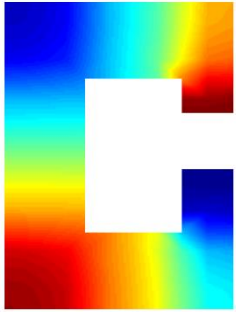
Mode shape 2

$\tau_2 < \tau_1$



Mode shape 3

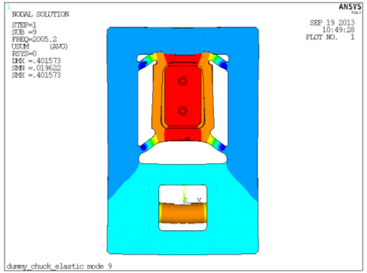
$\tau_3 < \tau_2$

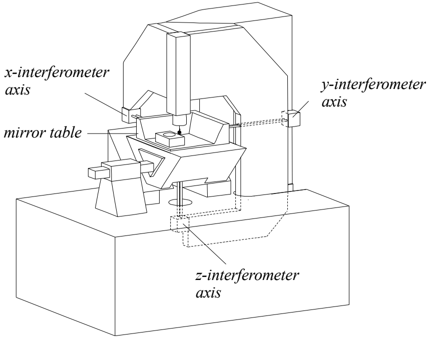


Mode shape 4

$\tau_4 < \tau_3$

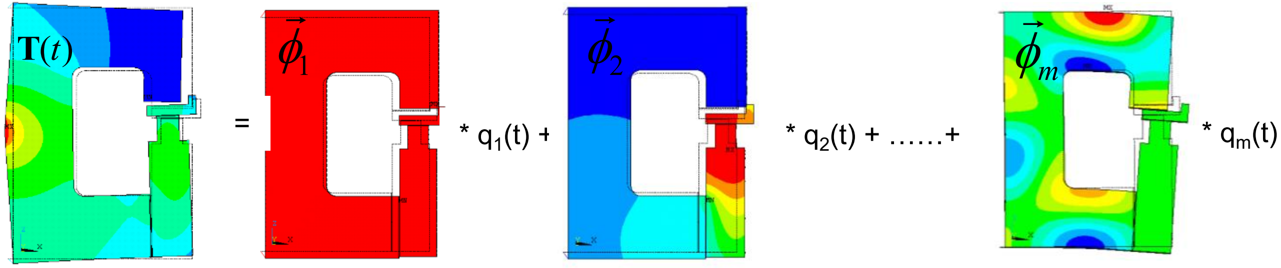
.....





Thermal Compensation strategies: Eigen modes

Arbitrary temperature field = sum of “Thermal Eigen-mode Shapes”:

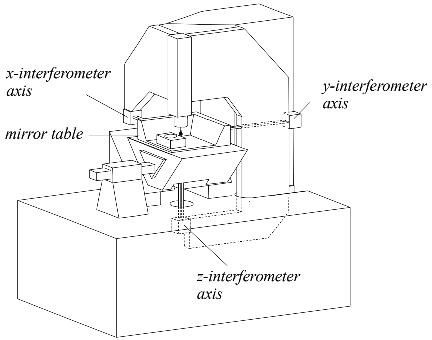


$$\bar{T}(t) = \bar{\phi}_1 q_1(t) \quad + \quad \bar{\phi}_2 q_2(t) \quad + \quad \cdots \quad + \quad \bar{\phi}_m q_m(t)$$

Thermal States

Temperature field

Thermal Mode shapes

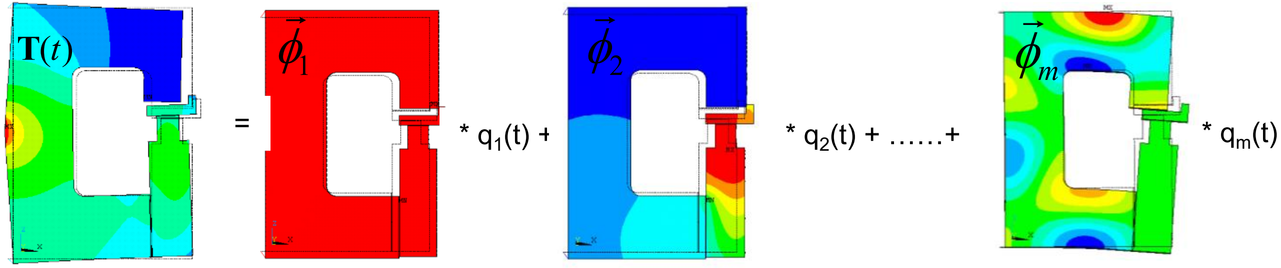


Which states (modes) are relevant?:

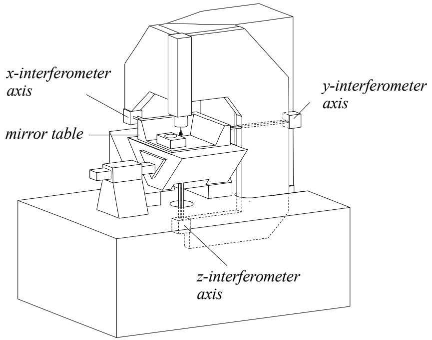
1. Model controlability
2. Model observability

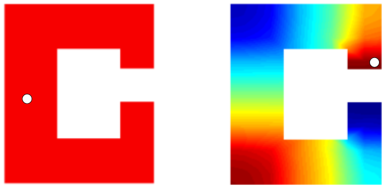
Thermal Compensation strategies: Eigen modes

Arbitrary temperature field = sum of “Thermal Eigen-mode Shapes”:



$$\bar{T}(t) = \bar{\phi}_1 q_1(t) \quad + \quad \bar{\phi}_2 q_2(t) \quad + \quad \cdots \quad + \quad \bar{\phi}_m q_m(t)$$

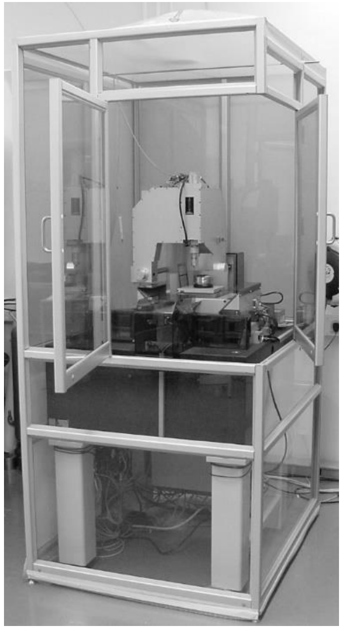


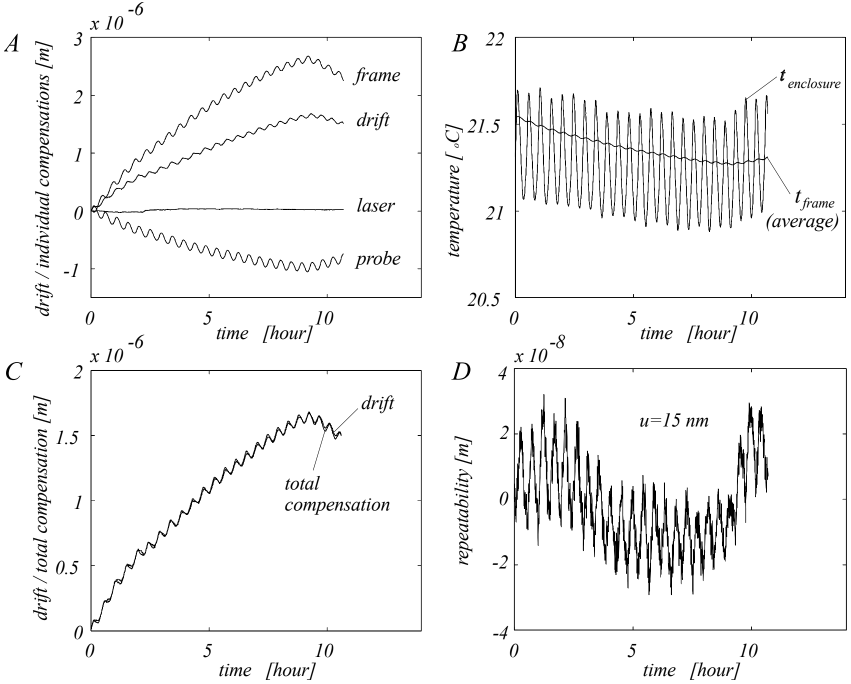


- Location of temperature sensors to identify relevant states $q_i, q_j \ldots q_k$
- Only these states are necessary to predict the relevant part of $\bar{T}(t)$

Thermal Compensation strategies

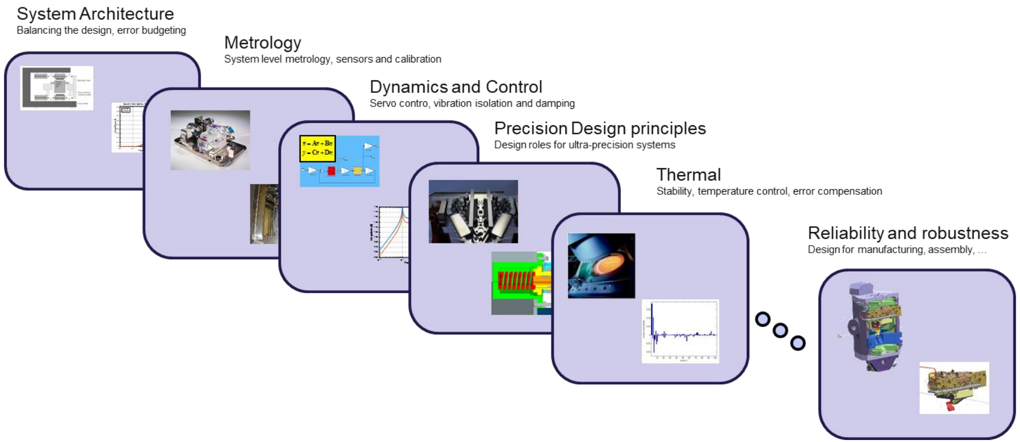
Example performance of thermal compensation model:
initial drift of ~1.7 um is reduced to ~ 15 nm

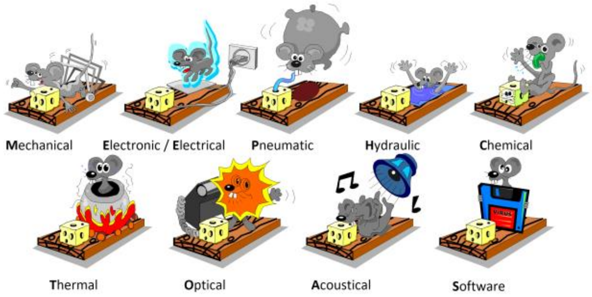




Summary

Design of ultra precision systems needs a system level mechatronics approach.





Next generation beam line equipment needs these design principles to reach the high dynamic and ultra-precision performances as required.

MI Partners
PARTNERS IN MECHATRONIC INNOVATION

www.mi-partners.nl

Habraken 1199
5507 TB Veldhoven
The Netherlands

T +31(0)40-2914920
E info@mi-partners.nl